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(54) Abstract Title
Structures with magnetic properties

(57) A surface structure with preselected magnetic permeability in the plane of the surface comprises an array of elements consisting of multi-turn helical loops made for example by tracks 10, 11 on a printed circuit board plated through for example by vias 13 and with the possible addition of a parallel capacitance 14, the pitch of the array being much less than the wavelength of the electromagnetic radiation to which the surface exhibits predetermined values of magnetic permeability, which can range from negative values such as -1 to 0 and to positive values greater than 1. The latter act as a duct for magnetic flux allowing receive coils and magnetic resonance imaging apparatus to be spaced from the surface of a patient and also to allow for screening purposes within magnetic resonance imaging apparatus. A value of magnetic permeability of -1 enables the surface structure to be used as a reflecting surface.

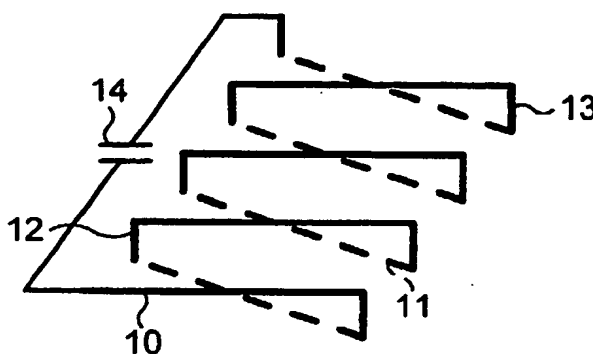


FIG. 6

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

The print reflects an assignment of the application under the provisions of Section 30 of the Patents Act 1977.

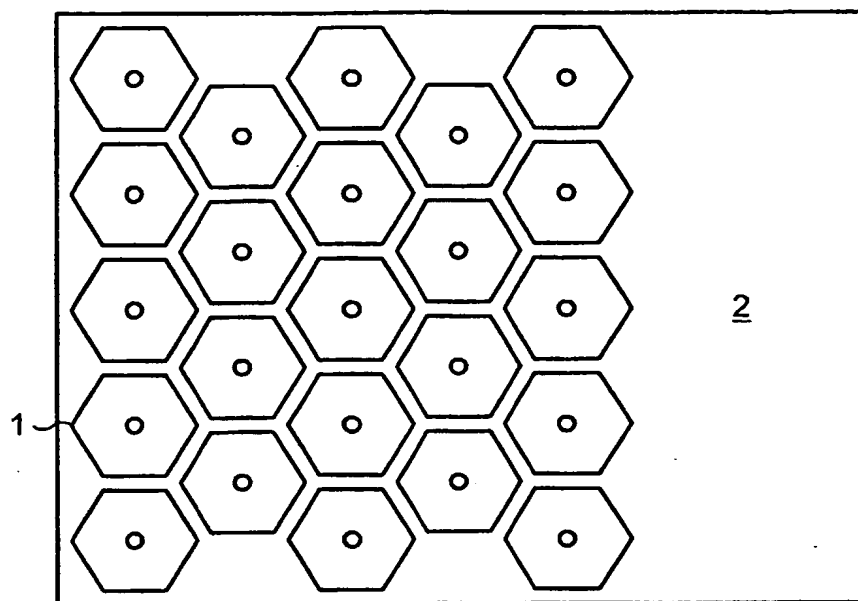


FIG. 1
PRIOR ART

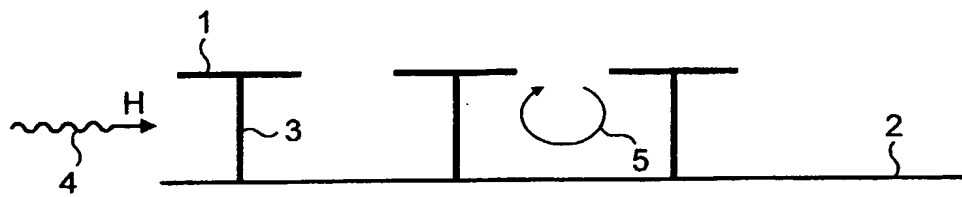
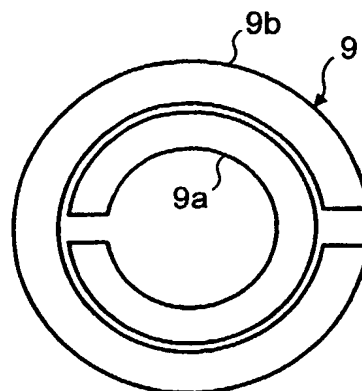
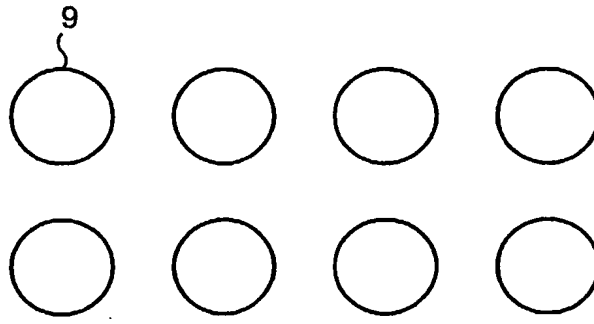
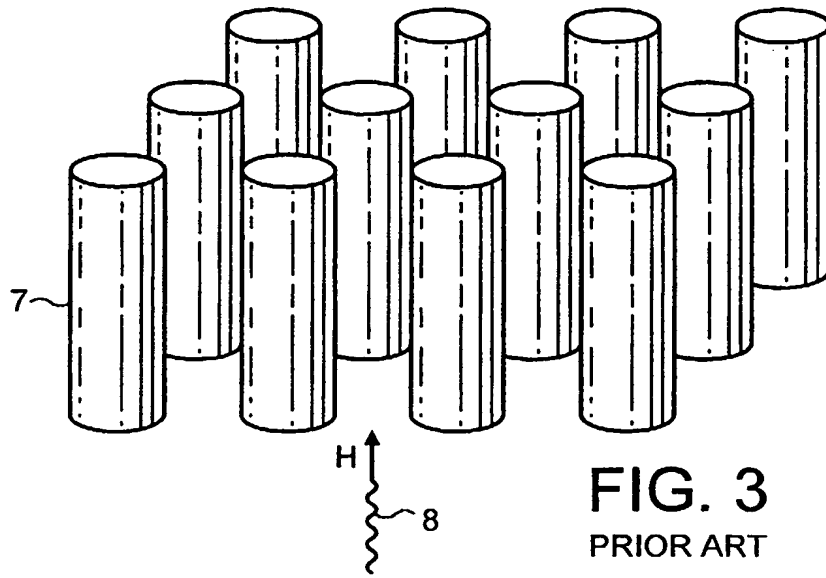
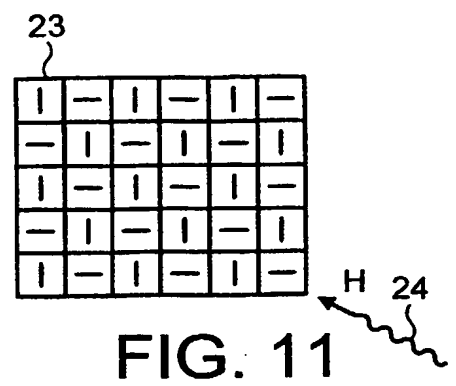
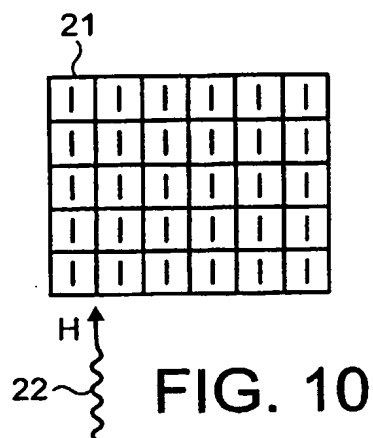
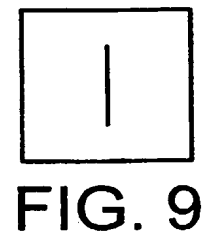
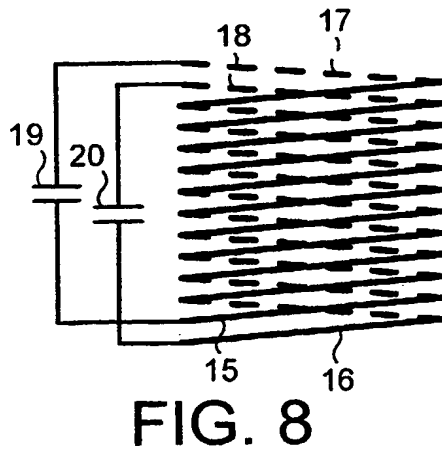
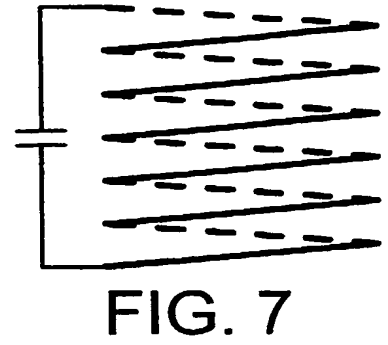
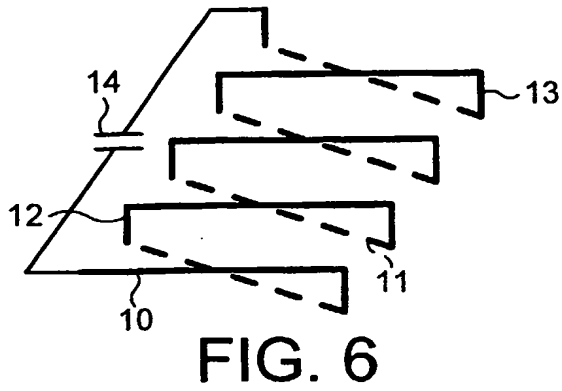


FIG. 2





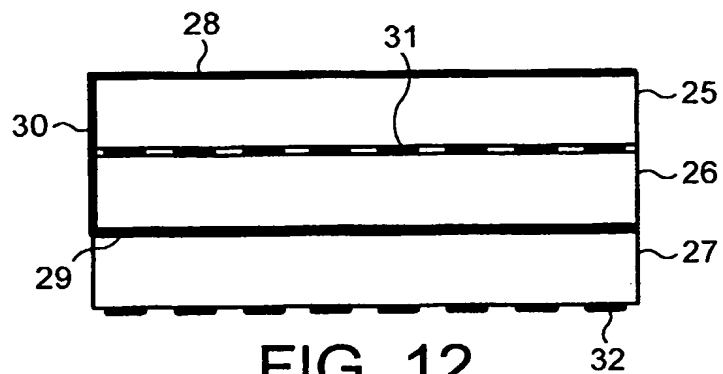


FIG. 12

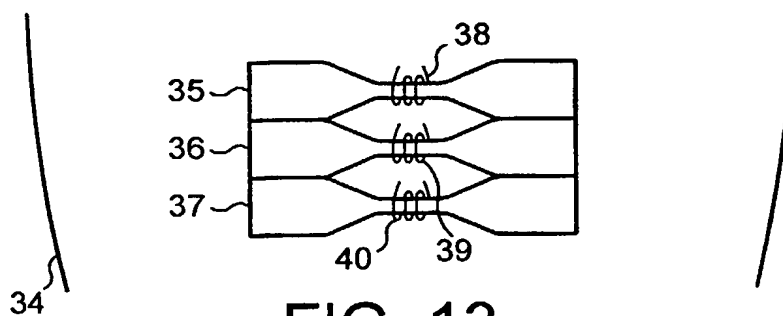


FIG. 13

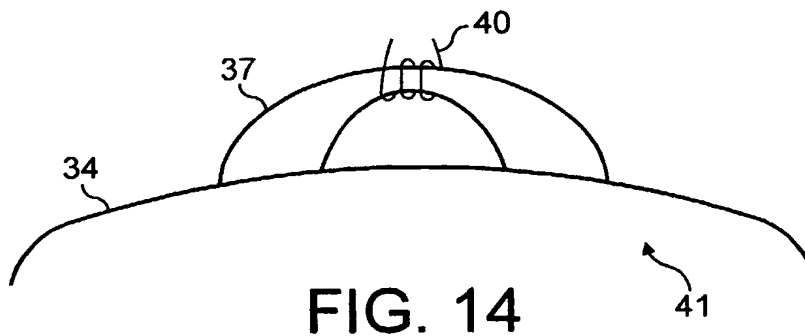


FIG. 14

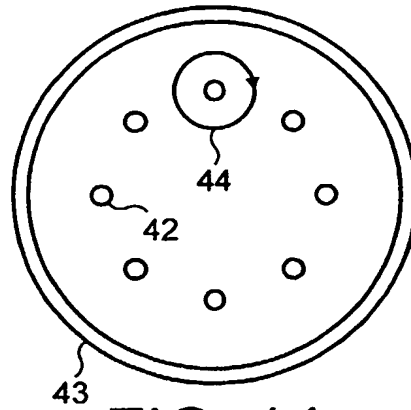


FIG. 14
PRIOR ART

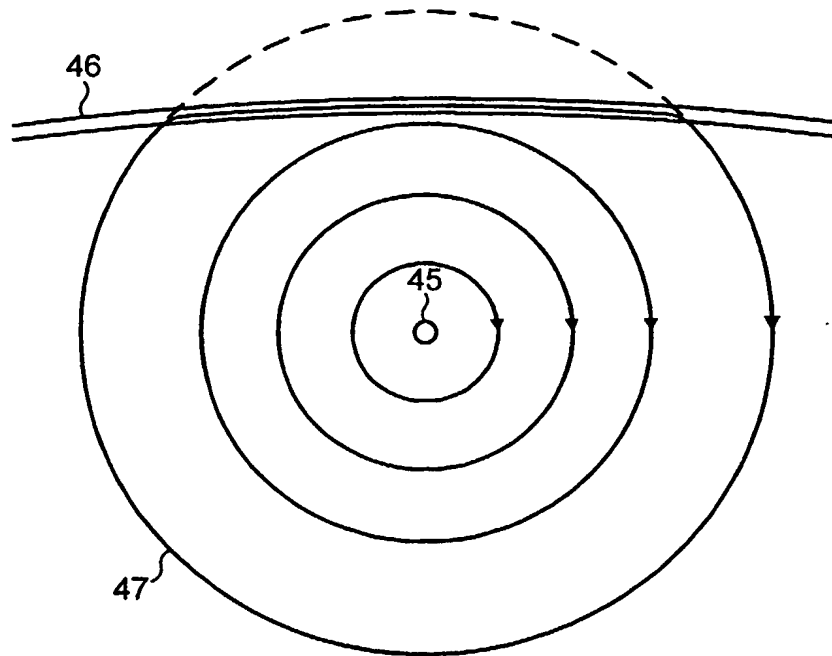


FIG. 16

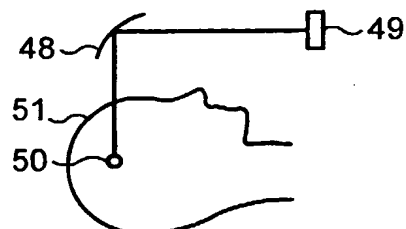


FIG. 17

STRUCTURES WITH MAGNETIC PROPERTIES

This invention relates to structures with magnetic properties.

A surface structure having magnetic properties for use at GHz (mobile phone) frequencies has been proposed (High-Impedance Electromagnetic Surfaces with a Forbidden Frequency Band, D. Sievenpiper, L. Zhang, R.F. Jiminez Broas, N.G. Alexopolous. E. Yablonovitch, IEEE Transactions on Microwave Theory and Techniques, 1999, 47, 2059-2074).

The surface is shown in plan in Figure 1 and in cross-section in Figure 2. The surface, which is fabricated as a printed circuit board, consists of a triangular lattice of hexagonal metal plates, connected to a solid metal sheet by vertical conducting vias. One of the plates is designated by the reference numeral 1, the solid metal sheet is designated by the reference numeral 2, and one of the vias is designated by the reference numeral 3. The surface structure has magnetic properties which can be tailored (specifically magnetic permeability) in the plane of the surface over a range of frequencies for which the wavelength is much greater than the period of the surface (so that the structure can be considered to be a homogeneous medium). The permeability varies with frequency and structural design, so the material can be tailored to have a specific permeability at a specific frequency. Since the protrusions 1 are small compared to the operating wavelength, their electromagnetic properties can be described using lumped-circuit elements – capacitors and inductors. There will be capacitance between adjacent plates 1 and circulating currents 5 giving rise to



inductance. The magnetic permeability is exhibited in any direction in the surface of the plane, i.e. radiation with the H-field having an in-plane component will interact with the material. These surface structures are sometimes referred to as magnetic conductors or magnetically conducting planes.

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A typical diameter of the metal plates 1 is around 3mm for operation at around 15GHz.

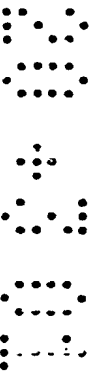
Such surfaces would be of interest for other applications at lower frequencies, for example, 20MHz. However, the dimensions of such a structure would render it too large for many applications.

10

A bulk structure having magnetic properties for use at GHz frequencies has been proposed (Magnetism From Conductors and Enhanced Non-Linear Phenomena, J.B. Pendry, A.J. Holden, D.J. Robbins and W.J. Stewart, 1999, 47, 2075-2084). In one form, an array of "Swiss roll" resonating structures (Figure 3), one of which is indicated by the reference numeral 7, has magnetic permeability which can be tailored in a direction parallel to the axes of the Swiss rolls i.e. for incoming radiation in the direction 8. The H-field must be parallel to the axes. Again, the range of frequencies over which the magnetic permeability is exhibited applies to wavelengths much greater than the spacing of the rolls. The structure can be considered to consist of lumped circuit resonant elements, inductance being provided by current circulating around the curved wall of the Swiss rolls, and capacitance being provided by the self-capacitance between the inner and outer ends of each roll. In another form, an array of split ring structure 9 arranged in a plane can be stacked to form an array of columns, and has

15

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magnetic permeability in a direction parallel to the axes of the columns. The split ring structures are not shown in detail in Figure 4, but one of the elements is indicated in Figure 5. Each element consists of an inner split ring 9a and an outer split ring 9b. Alternating electrical currents are induced in each ring 9a, 9b, in response to incoming radiation in a direction perpendicular to the plane of the array of rings, whose H-field is parallel to the axes of the rings and so couples to the rings. Despite the break in the slit ring structure, alternating currents can flow by virtue of the self-capacitance between the ends of each ring, and there is also capacitance between the inner ring 9a and the outer ring 9b.

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The array of split rings, and an array of spiral elements have, been proposed for use at MHz frequencies e.g. 21MHz (British Patent Application Nos. 0005352.0, 0005349.6), with an array spacing of the order of 6cm, and the multi-layer nature of the construction lends itself to the production of a surface structure. However, because the magnetic permeability takes place in the direction of the axes of the columns of rings, that is, perpendicular to the plane of the array, several layers are necessary to produce a useful value of magnetic permeability. Accordingly, the dimensions of the structure render it too large for many applications.

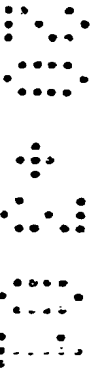
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The invention provides a surface structure with magnetic properties, comprising an array of elements having capacitance and inductance, the structure exhibiting a predetermined magnetic permeability, in the direction in which the surface extends, to incident electromagnetic radiation of a given wavelength greater than the spacing of the

elements, wherein the elements are in the form of conducting multi-turn helical loops arranged with their axes extending generally in the direction of the surface.

5 A greater inductance is possible for an element of a given loop size since the elements are multi-turn loops, leading to a reduction in the resonant frequency for the structure, which is related to the inverse of the square root of the inductance of the elements.

10 The invention also provides a surface structure with magnetic properties, comprising an array of elements having capacitance and inductance, the structure exhibiting a predetermined magnetic permeability, in the direction in which the surface extends, to incident electromagnetic radiation of a given wavelength greater than the spacing of the elements, wherein the surface structure is arranged to reflect RF flux.



Such a structure can be used as a reflector for RF flux.

15

The invention also provides magnetic resonance apparatus, especially magnetic resonance imaging apparatus, which uses a surface structure as defined above as a reflector to direct magnetic resonance signals to a receive coil.

20 Advantageously, the predetermined magnetic permeability is exhibited to incident electromagnetic radiation of a wavelength at least two times greater than the spacing of the elements, preferably at least five times greater than the spacing of the elements. There may be advantages if the wavelength is ten times or one hundred times the element spacing.

The invention will now be described in detail, by way of example, with reference to the accompanying drawings, in which:

Figure 1 is a plan view of a known surface structure with magnetic properties;

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Figure 2 is a front view of the surface structure of Figure 1 showing only the first line of plates;

Figure 3 is a schematic perspective view of a known bulk structure with magnetic properties;

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Figure 4 is a plan view of one layer of a known multi-layer bulk structure with magnetic properties;

Figure 5 is a plan view of one element of the array shown in Figure 4;

15

Figure 6 is a perspective schematic view of one element of a surface structure with magnetic properties in accordance with the invention;

Figure 7 is a plan view of the element shown in Figure 6;

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Figure 8 is a plan view of an alternative form of one element of a surface structure with magnetic properties in accordance with the invention;

Figure 9 indicates a symbol which represents the plan view of the forms of element shown in Figure 7 and Figure 8;

Figure 10 is a schematic view, using the symbol shown in Figure 9, of a uniaxial surface structure in accordance with the invention;

Figure 11 is a schematic view, using the symbol shown in Figure 9, of a biaxial surface structure in accordance with the invention;

Figure 12 is a schematic front view of another form of element of a surface structure with magnetic properties in accordance with the invention;

Figure 13 is a plan view of surface structures with magnetic properties in accordance with the invention, positioned for imaging above an abdomen;

15

Figure 14 is a front view of the surface structures shown in Figure 13;

Figure 15 is a schematic axial sectional view through a part of a magnetic resonance imaging apparatus employing a known RF screen;

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Figure 16 is an enlarged cross-sectional view, compared to Figure 15, of a part of a magnetic resonance imaging apparatus employing an RF screen in the form of a surface structure with magnetic properties in accordance with the invention; and

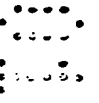
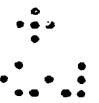
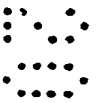


Figure 17 is a schematic representation of a reflecting surface in the form of a surface structure with magnetic properties according to the present invention forming part of magnetic resonance imaging apparatus.

- 5 Referring to Figure 6 and 7 of the drawings, one element having inductance and capacitance is illustrated, and a surface structure is made up of an array of such elements, for example a rectangular array of elements arranged in a plane.

Each element consists of a multi-turn helical loop of rectangular form. The loop is
10 made up of tracks 10 (shown in solid line) on the upper surface of a double-sided printed circuit board (not shown), tracks 11 (shown dotted) on the lower side of the printed circuit board, and vertical conducting vias 12, 13 completing the loops. The vias 12, 13 may be plated through or pinned connections. The element as described is
15 primarily an inductor, but does have some self-capacitance between the first and last turns of the loop. However, an additional capacitance 14 is connected in parallel with the loop. This capacitance may be surface mounted, for example.

The element thus described may be replicated over the surfaces of a double-sided printed circuit board, with the multi-turn loops being arranged with their axes parallel to
20 each other, to form a surface structure with magnetic properties according to the present invention.

The resonant frequency of each element is more or less proportional to the square root of the inverse of the product of the inductance and the capacitance (it being partly



- dependent on residual resistance), and the resonant frequency of the surface structure is influenced mainly by the resonant frequency of each element, although also partly by the arrangement of the elements in the form of the array. The capacitance 14 increases the product of the inductance and capacitance of the element, and therefore decreases its
- 5 inverse and the square root of its inverse, thereby lowering the resonant frequency for the surface structure. This resonant frequency, or more properly, band of frequencies, define the frequencies for which the surface structure has magnetic properties, that is, predetermined values of magnetic permeability. This varying magnetic permeability is exhibited for electromagnetic radiation that has a component of its H-field in the plane
- 10 of the printed circuit board, and parallel to the axes of the multi-turn loops. Over the range of frequencies for which the surface structure has magnetic properties, the H-vector predominates, and can be considered to be aligned with the direction of propagation of the electromagnetic radiation. The surface structure is thus uniaxial.
- 15 Typical dimensions for the form of elements shown in Figures 6 and 7, providing operation at a frequency in the region of 20MHz are: five turns of the loop with a surface track width of around 0.5mm and length around 25mm, on each side of a board which is 3.2mm thick bearing 2oz copper (per square foot, corresponding to approximately 70 μ m thickness), corresponding to the tracks being approximately 70 μ m
- 20 in thickness. The additional capacitance required is around 1.5nF.

In a second embodiment of element of the array, in Figure 8 a double-wound form of element is shown. Each of the windings is identical to those shown in Figure 6 and 7, but two such windings are placed closely adjacent to each other. This has the effect of

minimising the amount of external capacitance. Interleaving the windings increases the stray capacitance between the two, and the inductance is a function of the total number of turns (in both windings). The double wound structure provides more inductance, as there are more turns, more self-capacitance, from the side-by-side windings, and so a lower resonant frequency. Alternatively, for the same frequency, fewer turn are needed, resulting in smaller structures which can be more tightly packed to give bigger resonances.

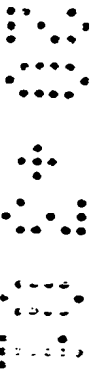
Thus, one multi-turn loop consists of tracks 15 on the top of the board and 18 on the bottom of the board, in parallel with capacitor 20, and the other multi-turn loop consists of tracks 16 on top of the board and tracks 17 on the bottom of the board connected to capacitor 19, the loops being connected by vertical connections, each loop being connected by vertical connections as for the element shown in Figure 6.

Using the symbol of Figure 9, which represents the elements of Figure 6 and 7 on the one hand and Figure 8 on the other hand, in the orientations shown in Figures 7 and 8, two possible surface structures are shown in Figures 10 and 11.

In Figure 10, a regular array of either form of element is formed on the double sided printed circuit board, with the loops running from side to side of the boards and the axes of the loop running from top to bottom of the boards. The board 21 exhibits magnetic permeability to incoming radiation in the plane of the board and in the direction 22, the H-vector being considered to be running parallel to the axes of the loops. With the board 23 (also flat) in Figure 11, alternate elements of the array are arranged at right

angles to each other, so that the axes of the loops are alternately arranged from top to bottom of the board, in the case of the top left element, from side to side of the board in the case of the second element from the left in the top row, etc. Such a surface structure exhibits magnetic permeability in two directions at right angles in the plane of the board, and is thus biaxial. It follows that magnetic permeability is exhibited in any direction in the plane of the board.

The spacing of the elements of the array may be less than half the wavelength in the predetermined band at which the predetermined magnetic permeability is exhibited, and preferably less than a fifth or less than a tenth of that wavelength. The magnitude of the magnetic permeability, and the band of frequencies over which the predetermined magnetic permeability is exhibited, is largely dependent on the inductance and capacitance of each resonant element, but these quantities will also change a little when the spacing of given elements is changed.



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In other words, changing the pitch acts on two aspects of the performance. More turns per unit length increases the self-inductance and hence reduces the resonant frequency. More elements per square centimetre means a higher packing density, and so a larger excursion in the permeability curve i.e. large values of permeability become available.

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Referring to Figure 12, an alternative form of element is shown. These are also arranged in any array (not shown) like those in Figures 10 and 11. This consists of a multi-layer board, the layers being 25, 26 and 27. The layer 25 has tracks 28 running from side to side of the board on its upper surface, and tracks 31 running from front to

back of the board, on its lower surface, into the plane of the paper as seen in Figure 12. A spacer 26 spaces the board 25 from a board 27 which has tracks 29 running from side to side of the board on the top and tracks 32 running from front to back (into the plane of the paper) on its lower surface. The tracks 28 and 29 are connected by vias such as 5 30 and the tracks 31 and 32 are connected at the front and back of the board by vias (not shown). It will be seen that each element consists of a loop of the form shown in Figure 6 interleaved with another loop of the form shown in Figure 6 which remains in the same plane but has been turned around through 90°. Thus, each element exhibits magnetic permeability in any direction in the plane of the board. Additional capacitance 10 can be provided by surface mount capacitors on the top of the board for the turns defined by the tracks 28, 29 and on the lower surface of the board by the turns defined by the tracks 31 and 32. This corresponds to the arrangement of Figure 11 but each element is biaxial, resulting in a greater packing density. This is desirable to improve magnetic permeability performance in the plane. The inductance and capacitance which 15 control the resonance arise from the winding regarded as a whole, while any in-plane flux couples with the winding. A stronger resonance will be provided, and hence a wider range of frequencies.

The magnetic permeability normal to the surface structures described is unity i.e. that of 20 free space.

Of course, variations may be made without departing from the scope of the invention. Thus, there is no need for the loops to be of the rectangular form shown. Other rectangular dimensions are possible and, indeed, on a suitable mount, the loops need not

be rectangular at all, they could be circular arranged on cylindrical mounts. There is no need for the tracks to be plated onto the board, winding of wires would be possible for the elements. While a large plane surface structure could be made from an array of the elements as described, there may be instances where a non-planar surface is desirable.

- 5 Thus, a dished shape of surface could be provided by arranging for the surface to be made up of relatively small elements such as shown in Figures 10 and 11 of flat shape. Another possibility would be for a board to be fabricated to a desired curved shape, for example in the case of a reflector, designed to focus radiation emanating from a particular region to another region, and the elements could then be printed onto this
- 10 curved surface.

While the elements have been shown in conjunction with additional capacitance, there may be circumstances where this could be dispensed with, relying on the self-capacitance of the multi-turn loops.

15

- While the surface structures described exhibit predetermined values of magnetic permeability primarily in the HF band (wavelength 10m-100m), the surface structure would also exhibit magnetic permeability in the MF band (wavelength 100m-1000m), and in the VHF and UHF bands (wavelength 1m-10m and 0.1m-1m), and higher
- 20 frequencies.

The pitch spacing is less than the wavelength at which magnetic permeability is exhibited, and is preferably less than at least one tenth of that wavelength.

The bandwidth over which the magnetic permeability varies depends on the balance of inductance and capacitance, and is defined by the width of the resonance (determined by the dissipation or damping in the structures, and mainly due to the resistance of the loops), and by the strength of the resonance, determined by the packing density of the loops.

The surface structures described could have magnetic permeabilities which are positive and greater than unity, preferably which range from 4 to 5 and upwards, to act as a duct, in the manner described in our co-pending British Patent Application No. 0005349.6, zero value or negative value as described in our British Patent Application No. 0005352.0 in order to act as a screen, or the value of -1 as described in British Patent Application No. 0015067.2.

One example of a flux guide is shown in Figures 13 and 14, in which a portion of a human abdomen 34 is illustrated, in the imaging region of magnetic resonance imaging apparatus.

In order to image a sensitive region 41, instead of a surface coil being placed on the nearest region of the surface of the patient, paddle-shaped flux guides 35, 36, 37 are placed on the surface of the patient in order to duct flux from the regions of the ends of the guides through the guides and, in particular, through the narrow neck region at which a receive coil 38, 39, 40 is wound, where the magnetic resonance signal may be picked up.

There are two advantages of such an arrangement. The receive coils 38 to 40 are spaced from the surface of the patient and can therefore be refrigerated. Secondly, the region of the patient immediately above the sensitive region 41 is left free in order for possible invasive surgery to take place which can be monitored in real time by viewing the magnetic resonance image. Another advantage is that there is no mutual inductance between the guides 35, 36, 37, allowing the receive coils to be used in conjunction with techniques which use an array of coils to enable image space to be undersampled by relying on coil relative position and sensitivity profiles to generate missing data (Simultaneous Acquisition of Spatial Harmonics (SMASH): Fast Imaging with Radio Frequency Coil Arrays, Daniel K Sodickson, Warren J Manning, MRM38: 591-603 (1997)).

Typical values of the magnetic permeability are in excess of 4.

As an alternative to the ducting arrangements of Figures 13 and 14, the surface structure of the invention may be used for screening.

Thus, referring to Figure 15, which represents a magnetic resonance imaging apparatus, magnetic resonance is excited in a whole body typically using a so-called birdcage coil, consisting of a number of conductors 42 which extend along the surface of a notional cylinder and are joined by rings at each end of the notional cylinder. This is used to generate RF excitation pulses to excite resonance in a sensitive region being imaged. Clearly, such a birdcage coil will also emit RF radiation outwardly as well as inwardly to the desired region, and such radiation would couple with the metal of the imaging

apparatus surrounding the coil, which would distort the RF magnetic fields and affect machine performance. For this reason, it is standard practice to employ a mesh screen 43 to dissipate the power from the RF pulses through eddy currents in the screen. In practice, such a conventional screen cannot be too close to the conductors since then
 5 most of the RF power is dissipated in the screen.

Referring to Figure 16 which is on a greatly enlarged scale compared to Figure 15, a single conductor 45 of a birdcage coil is shown and a surface structure of the present invention used as a screen 46, circular like that of Figure 15, is arranged more closely
 10 adjacent thereto than is the screen 43 of the prior art arrangement of Figure 15. The surface structure 46 acts as a flux guide, so that, as far as the flux line 47 is concerned, there is a lower reluctance path along the guide than along the path (shown dotted) it would have taken if the screen were not present.

15 Typical magnetic permeabilities for this case would be substantially greater than 1, preferably greater than 2, advantageously greater than 4.

One advantage of the screening surface structure 46 is that the structure can be placed nearer to a conductor 45 of the birdcage coil than hitherto. A second advantage is that
 20 the flux is ducted around the screening surface structure, rather than being dissipated, so that less power is needed in the means to generate the RF excitation pulse.

A surface structure which acts as a mirror is shown in Figure 17 where surgery is to be carried out on a region such as 50 on the cranial region of a patient 51. A surface

structure according to the invention 48 used as a mirror may be used to reflect magnetic resonance signals received from the sensitive region 50 onto a receive coil 49 spaced away from the surface of the patient. The advantage of this is that the receive coil 49 is not in contact with the surface of the patient, which is a very great advantage if the
 5 imaging operation is to be performed at the same time as surgery, where maintenance of sterile conditions is very important.

The value of magnetic permeability to which the surface structure would be tuned in the case of Figure 17 would be -1 .

10

The patient shown in Figure 17 is positioned in magnetic resonance imaging apparatus, and magnetic resonant active nuclei in a sensitive region in which a large, constant, magnetic field is set up, such as the region 50, are excited by an RF excitation pulse, enabling magnetic resonance signals representative of the excited region to be
 15 generated. These are detected by the receive coil 49.

20

The surface structure 48 behaves like a mirror provided the RF flux is reflected at grazing or near grazing incidence (in the region of less than 15° away from the grazing incidence). Normally incident radiation will go straight through the surface structure. The surface structure can thus be likened to the optical reflecting properties of a block of glass.

At near grazing incidence, the magnetic permeability could be a substantial, positive, value, and the surface structure would still work as a reflector, but in this case, the

radiation will tend to be ducted through the material, rather than being reflected by it (as in the case described of a value of -1 for the magnetic permeability).

5 The surface structure can be used for reflecting received magnetic resonance signals to a receive coil, or for reflecting the excitation pulses to a sensitive region. More generally, the reflecting surface could be used whenever it is desired to direct RF flux, for example, where it is desired to heat tissue to destroy it for treatment purposes.



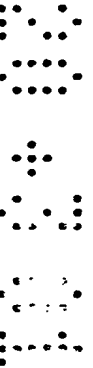
the respective elements of the second array, and respective elements of each array being superimposed.

13. A surface structure as claimed in any one of Claims 1 to 12, in which the surface is plane.

14. A surface structure as claimed in any one of Claims 1 to 12, in which the surface is curved.

15. A surface structure as claimed in Claim 2, in combination with a receive coil of magnetic resonance apparatus.

16. A surface structure substantially as herein described with reference to the accompanying drawings.





INVESTOR IN PEOPLE

Application No: GB 0105480.8
Claims searched: 1-16

Examiner: Peter Emerson
Date of search: 4 October 2001

Patents Act 1977 Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.S): H1Q QEJ, QEX; H1W WBA, WBX, WGX, WHA, WWX; H1R RBH

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H01Q 1/52, 15/14, 17/00

Other: Online: WPI, JAPIO, EPODOC, INSPEC, IEL

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
A	GB 2360137 A (MARCONI)	
X	IEEE Transactions on Microwave Theory and Techniques, Vol 47, No 11, pp 2059-2074, Nov 1999, Sievenpiper et al.	2, 13

X Document indicating lack of novelty or inventive step
Y Document indicating lack of inventive step if combined with one or more other documents of same category.

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P Document published on or after the declared priority date but before the filing date of this invention.
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